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Initial Analysis of NAVSTAR Vehicle 38 Calorimeter Test Data

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This report presents an analysis of the first three months of calorimeter data from the NAVSTAR vehicle 38 solar array contamination flight test. The conclusion of this preliminary analysis is that the calorimeters' solar absorptances are increasing at a rate of several percent (absolute value) per year. These values are consistent with the observed ~2% per year anomalous solar array power loss.

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1. Introduction

Spacecraft function in a hostile environment of vacuum, sunlight, natural radiation, and self contamination. They are fabricated in facilities of variable cleanliness. Contamination, deposited during manufacture, integration, and launch, and from long-term on-orbit outgassing can degrade the performance of spacecraft surfaces. In particular, optical surfaces, thermal control surfaces, and solar power arrays can all be affected adversely by the accretion of molecular contaminant films.

Figure 1 shows the power production capability of some of the GPS Block II and IIA satellites.[1] The five GPS Block I satellites whose power production capabilities were analyzed showed similar behavior.[2] After eight years on orbit, the GPS Block I solar arrays had suffered twice as much degradation in power production capability than was predicted pre-flight.

The GPS program followed good practices in selecting materials for space flight. However, analyses performed by both The Aerospace Corporation and the GPS Prime Contractor (Rockwell International, now Boeing North American, or BNA) identified photochemical contamination deposition as the origin of the problem. Furthermore, the vehicle vents most likely to be the sources of contamination were identified. To date, a redesign of the venting system of the Block IIA vehicle has not provided a solution to the problem, but there is still general consensus that contamination is the culprit.*

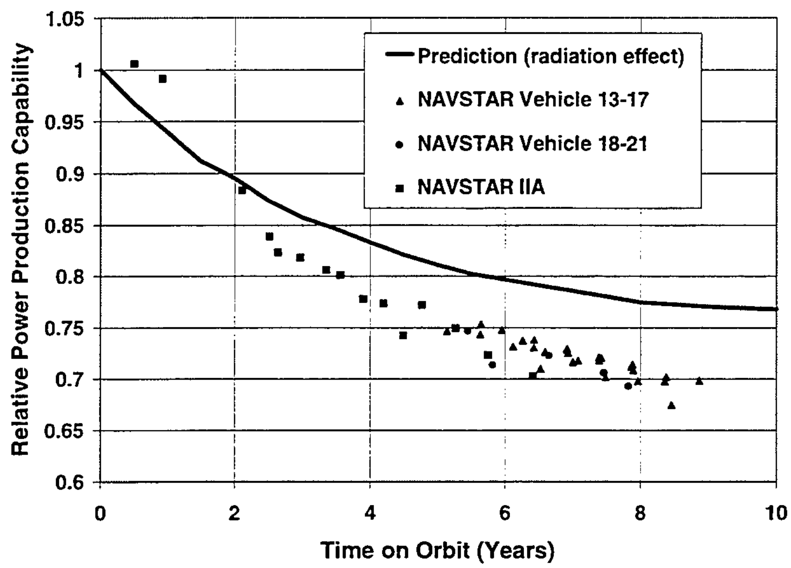

Figure 1. Power production capability of GPS block II and IIA satellites.

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*The reader should be aware that the GPS Block I satellites far exceeded their design life, and the Block II and IIA power systems are expected to meet their required mission duration because of adequate BOL margins.

2. GPS 38 Calorimeter Test

A "calorimeter" test was flown on NAVSTAR vehicle 5 to aid in improving the performance of battery radiators for the Block I satellites.[3] This test provided invaluable evidence to support the proposed contamination-induced degradation mechanism for Block I satellites. Therefore, the GPS Joint Program Office (JPO) decided to fly a calorimeter test in the final GPS IIA vehicle, NAVSTAR vehicle 38, that was launched from Cape Canaveral Air Force Station on November 5, 1997. The goal of this test is to provide confidence that the contamination hypothesis is the correct explanation of the anomalous loss of power production capability on GPS Block I, II, and IIA satellites.

The fielding of this flight test was a cooperative effort involving the GPS JPO, The Aerospace Corporation, and Rockwell International (now BNA). The calorimeters used in this test are basically of the "Reichard and Triolo" design.[4] Figure 2 is a photograph of one of the flight units. This very simple, flight-proven device comprises a fused silica optical solar reflector disk, mounted with a high degree of thermal isolation. The temperature of the sample disk is monitored with a thermistor, identical to those used in the GPS analog telemetry system.

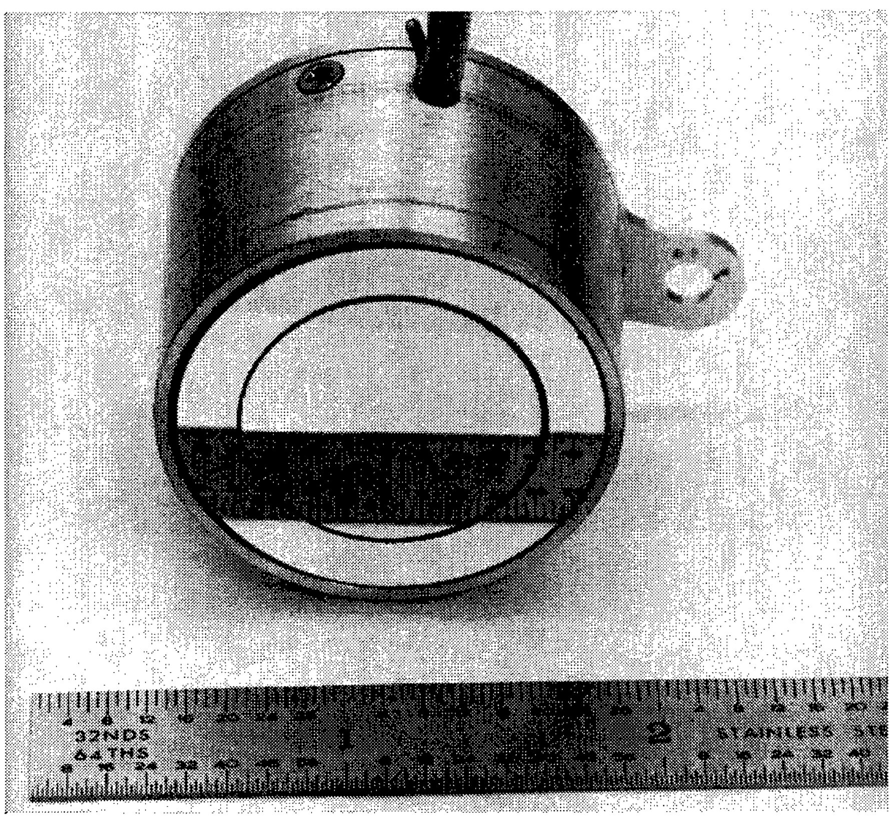

Figure 2. "Reichard and Triolo Calorimeter" for the GPS 38 solar array contamination test.

The hemispherical reflectances of the calorimeter disks were measured from 250 to 2500 nm with a Perkin-Elmer Lambda 9 spectrometer using a Labsphere 6-in. Spectralon-coated integrating sphere. The accuracy of the reflectance measurement is ~2%. The solar absorptances of the samples were calculated by trapezoidal integration over the air mass zero solar spectrum, per ASTM E490. The results of these measurements are shown in Table 1. Gilmore quotes a beginning-of-life value of 0.06 for the solar absorptance of 0.008" fused silica optical solar reflectors.[5]

No preflight data were obtained for the hemispherical emittance of the calorimeter test samples. After-the-fact measurements on spare material confirmed that they are 0.008" thick mirrors. Gilmore quotes a value of 0.80 for the hemispherical emittance of an 0.008" OSR.[5] The flight spare calorimeter's emittance was measured by Mr. Charles Smith of Boeing North American in Huntington Beach, CA, using a Gier-Dunckle DB-100 instrument. He reported an emittance value of 0.80 for the spare calorimeter.

Table 2 shows the beginning-of-life (BOL) calorimeter test surface properties used in this analysis.

The Reichard and Triolo calorimeter design has a long flight heritage. However, it is not perfect: there is "leaking" of heat to and from the disk sample. The magnitude of the heat leaks for the flight calorimeters was measured by placing the calorimeter in a known steady-state thermal environment and evaluating the deviation of its performance from ideality. The magnitude of the normalized heat leak ($Q/A\varepsilon$) is about 10–20 W/m^2 when the temperature difference between the sample disk and the substrate is about 60°C.

Table 1. Preflight Solar Absorptance Measurements

		Solar Absorptance		
Cal S/N	Mnemonic	measured range	max	min
3	H172	0.064	0.101	0.062
4	E142	0.067	0.102	0.067

measured range: 250-2500 nm
max: assumes 100% absorption outside measured range
min: assumes 0% absorption outside measured range

Table 2. BOL Properties Used for Calorimeter Data Analysis

Property	Abbreviation	Value
Solar Absorptance	α_s	0.07
Hemispherical Emittance	ε_h	0.80

3. NAVSTAR Vehicle 38 Calorimeter Telemetry Data

Figure 3 presents a schematic representation of the locations of temperature telemetry points on the GPS 38 satellite. This first analysis of calorimeter data relies on the filtered telemetry database from the Boeing North American Mission Operations Support Center (MOSC), in Seal Beach, CA, for the period November 14, 1997 through February 11, 1998.

Figure 4 shows the temperatures reported for the calorimeter mounted on the solar array boom located on an element known as the "J box" and solar array-mounted calorimeter. Two features of these plots indicate that the calorimeter test promises to produce good results

1. At the beginning of the test, the two calorimeters were approximately 50°C colder than their mounting surfaces, indicating that they maintained thermal isolation after launch.

2. The calorimeters show a discernible increase in temperature over the first three months of flight, while the related solar array temperatures (not shown) were constant.

The solar array mounted calorimeter data shown in Figure 4 seem noisier than the other temperature data. Inspection of other telemetry data showed that this "noise" is in fact a correlation between the solar array angle position and the calorimeter temperature. The likely origin of this correlation is a differing radiant heat load from the spacecraft body to the calorimeter with differing solar array position. It is reasonable that the boom calorimeter, being on the center line and being mounted further from the vehicle body, would show a smaller effect.

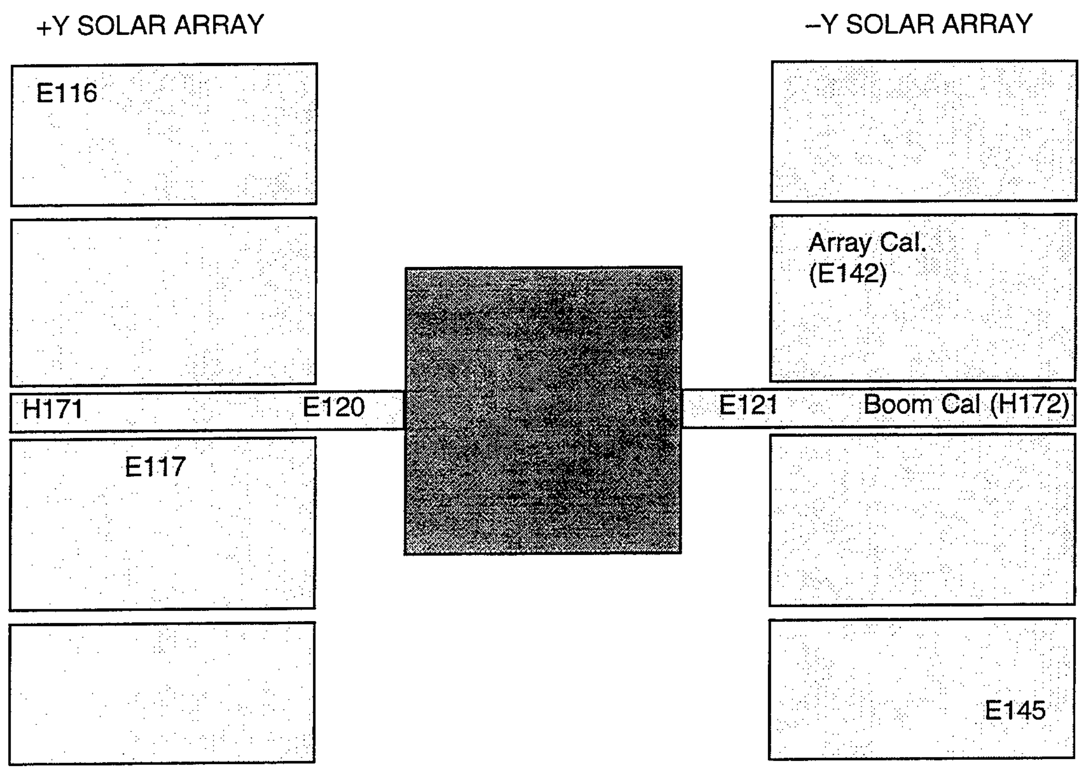

Figure 3. Schematic representation of selected GPS EPS telemetry points.

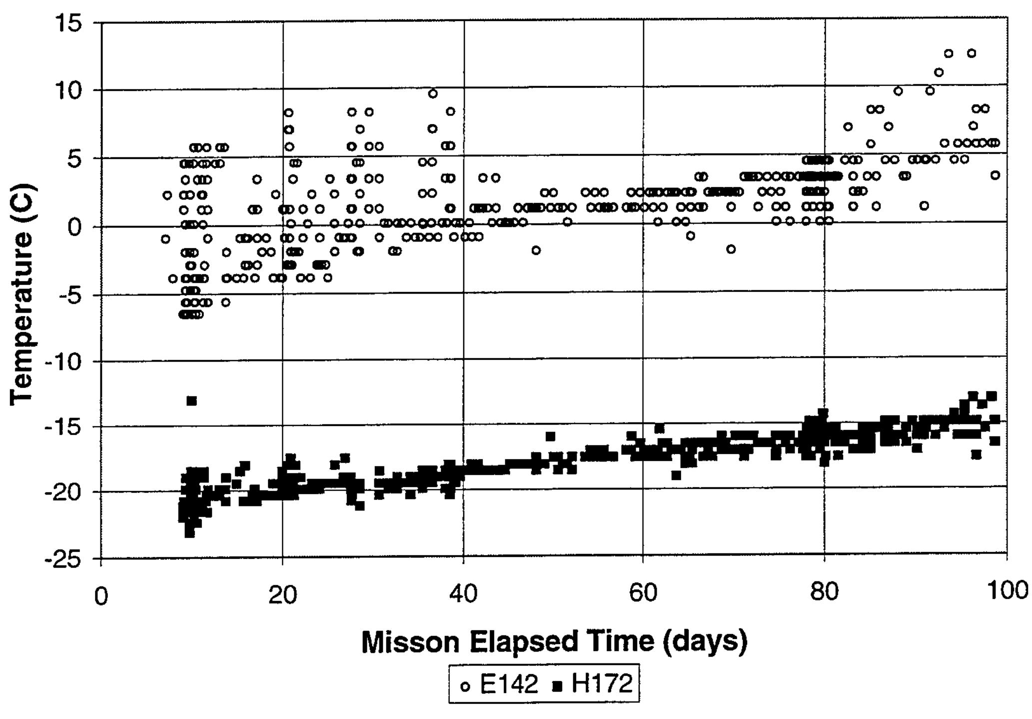

Figure 4. NAVSTAR Vehicle 38 calorimeter temperature data.

4. Orbital Data Analysis

The GPS 38 calorimeters are mounted on the -Y solar array, which continuously points at the sun. Thus, the steady-state heat flow equation for the calorimeter disks is

$$I_S \alpha_S A = A \varepsilon_h \sigma T^4 + Q \quad , \tag{1}$$

where A is the calorimeter area, and I_s is the solar flux, ~1351 W/m^2. In this case, the heat leak, Q, is the sum of all heat flow not arising from direct solar illumination or thermal emission from the calorimeter disk.

Using Eq. (1), the BOL temperatures, and the thermo-optical properties shown in Table 2, one can calculate the parasitic heat leak initially on orbit. The results are shown in Table 3. The inferred heat leaks are about a factor of 10 greater than the expected conduction-related heat leak inherent in the calorimeters (See above). This implies that the on-orbit heat leaks are dominated by radiation from the spacecraft body. Therefore, for this first analysis of GPS 38 calorimeter data, the heat leaks are taken to be constant, at the values shown in Table 3, over the ~100-day period for which data are evaluated. The high degree of correlation between solar array angle and array calorimeter temperature is further support for the assumption that satellite radiation dominates the heat leak term on orbit.

All of the boom calorimeter data were used in this analysis. The array calorimeter data were manually filtered to suppress the solar array angle effect. The results are shown in Figure 5. Also shown in Figure 5 are straight-line fits to the inferred solar absorptance values vs. time on orbit. The array calorimeter's solar absorptance appears to be increasing at about 9% per year. The boom calorimeter absorptance appears to be increasing by about 5% per year.

Table 3. Magnitude of the Nominal Orbital Heat Leak Values for Calorimeter Data Analysis

Calorimeter Location	Telemetry Mnemonic	BOL Temperature (°C)	Parasitic Heat Load ($Q/A\varepsilon$, W/m^2)
-Y Inboard Panel	E142	-3.5	181.5
-Y Solar Array Boom	H172	-20.6	112.5

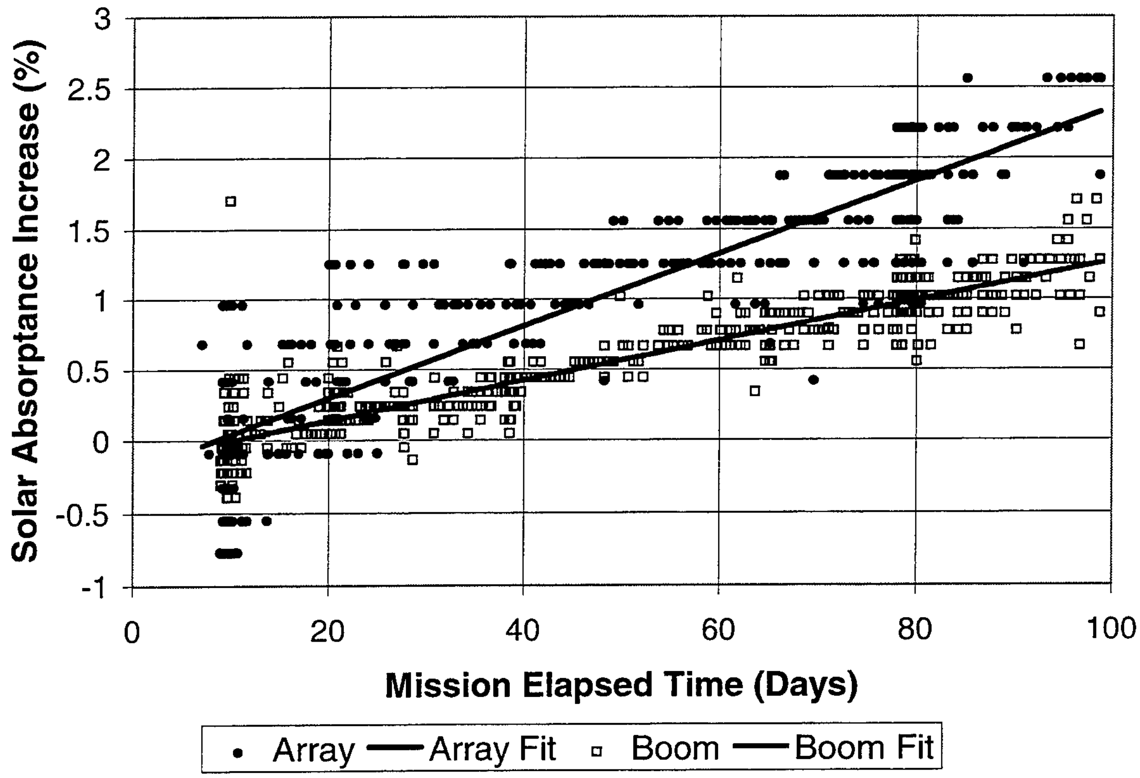

Figure 5. Estimated solar absorptance increase for GPS 38 calorimeters.

5. Summary

A first-order analysis of the first three months of calorimeter data from the NAVSTAR vehicle 38 solar array contamination flight test has been made. The preliminary conclusions are:

- The solar absorptance of the calorimeters is increasing at a rate consistent with the ~2% per year anomalous power loss, considering that the calorimeters are colder than the solar arrays and that a contamination effect on a mirror will be roughly twice the effect on a solar array.

- The inboard calorimeter appears to be darkening faster than the outboard calorimeter, even though it typically operates at higher temperature. This is consistent with a contamination phenomenon, where the flux of contaminants near the vehicle is greater than the flux at a distance from the core vehicle.

The absolute values of absorptance and the last observation must be considered tentative, pending a more refined analysis of these and additional data acquired throughout the first year of flight. However, if further analysis confirms these observations, then the GPS 38 calorimeter test is providing very strong evidence that contamination is the cause of anomalous degradation in power production capability on GPS Block II and IIA satellites. Confirmation of this conclusion will provide confidence that the steps taken to reduce contamination effects on GPS IIR and IIF solar arrays will produce a more robust electrical power system for the NAVSTAR satellites.

In addition to helping confirm the understanding of the performance of the electrical power system on GPS IIA satellites, these results also show clearly the utility of onboard monitoring of contamination effects for long-life satellites. Such monitoring is of particular value early in a "block" of satellites to confirm design analyses and provide early indication of end-of-life performance of contamination-sensitive subsystems and payloads.

References

1. A. C. Tribble, "Revised Estimates of Photochemically Deposited Contamination on the Global Positioning System Satellites," *J. Spacecraft*, 35, 114-116, 1997.

2. T. B. Stewart, G. S. Arnold, D. F. Hall, D. C. Marvin, W. C. Hwang, and R. D. Chandler, "Photochemical Spacecraft Self Contamination: Laboratory Results and Systems Impacts," *J. Spacecraft*, 26, 358-399, 1989.

   A. C. Tribble and J. W. Haffner, "Estimates of Photochemically Deposited Contamination on the GPS Satellites," *J. Spacecraft*, 28, 222, 1991.

3. W. R. Pence and T. J. Grant, "α_s Measurements of Thermal control Coatings on NAVSTAR Global Positioning System Spacecraft," *Progress in Astronautics and Aeronautics: Spacecraft Radiative Transfer and Temperature Control*, 83, T.E. Horton, ed., AIAA, New York, 234-246, 1982.

4. P. J. Reichard and J. J. Triolo, "Preflight Testing of the ATS-1 Thermal Coatings Experiment," in *Thermophysics of Spacecraft and Planetary Bodies*, G. B. Heller, ed., Academic Press, NY, 491-513, 1967.

5. D. G. Gilmore, *Satellite Thermal Control Handbook*, The Aerospace Press, El Segundo, CA, 1994.

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